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GENERAL ELECTRIC Review

A monthly magazine devoted to technical subjects of interest to the electrical profession.
Published by Publicity Department, General Electric Co., Schenectady, N. Y.
Subscription price $3. Single copies 30 cents.

Air Conditioning

Application of Refrigeration to Heating and Cooling of Homes

By
A. R. STEVENSON, Jr., F. H. FAUST and E. W. ROESSLER

REPRINT

From issue of March, 1932
Vol. 35, No. 3, Pages 145-153 Incl.

Editorial

PUTTING IDLE B.T.U'S. TO WORK

In the following article the principles of application of the refrigerator heat pump are outlined by A. R. Stevenson, Jr., F. H. Faust, and E. W. Roessler.

The concept of a heat pump is not difficult for the engineer who is familiar with thermodynamics, but it may be somewhat confusing to engineers trained in other lines and to laymen. A brief nontechnical explanation of the principle involved should make it clear how such a pump can abstract heat from a low-temperature level and transfer it to a higher-temperature level. Reference will be made to the electric refrigerator as an example of a heat pump.

The first concept necessary is that heat exists at all temperatures above absolute zero. No one has ever been able to reach this theoretical absolute zero value, but scientists have been able to predict it and to approach it within a few degrees. Ordinary atmospheric temperatures are far above zero on the absolute scale. In order to convert Fahrenheit temperature to the absolute scale it is necessary to add 460 deg. to the Fahrenheit reading. Thus a temperature of 70 deg. F. is equivalent to 530 deg. F. absolute, and a temperature of 35 deg. F. is equivalent to 495 deg. F. absolute. When 35 deg. F. outside temperature is referred to the absolute scale, it is immediately apparent that the air at this temperature has a comparatively high heat content even though it feels uncomfortably cool. In fact, the comfortable temperature of 70 deg. F. is only seven per cent higher on the absolute scale than the comparatively chilly temperature of 35 deg. F. whereas it is double 35 deg. F. on the ordinary Fahrenheit scale.

The second concept necessary is that heat always tends to flow from a higher temperature to a lower temperature. This is a common experience and is so well known that we may find it difficult to understand how heat at a low temperature level can be used for heating at a higher temperature level.

The explanation lies in the third concept that heat can be made to flow from a lower temperature to a higher temperature provided work is done on the medium containing the heat. The following analogy will illustrate this point. Water which has flowed downhill can be returned to a higher level by doing work on it. Likewise, heat can be returned to a higher temperature by doing work on the medium that conveys it.

A refrigerator for heating or cooling houses would not differ in essential principles from the ordinary electric refrigerator used for cooling foods. Both are essentially heat pumps and the house cooler is only an expanded form of domestic refrigerator. The operating cycle in the electric house cooler can be illustrated as follows: On a warm summer day with an outside temperature of 85 deg. F. and a house temperature of 70 deg. F. there would be a constant leakage of heat into the house from outdoors, but inside the house there could be placed a cold spot with a temperature of perhaps 50 deg. F. to which the heat would pass.

This cold spot would be the evaporator of the refrigerating apparatus, which in the ordinary refrigerator is the cold chamber where the ice cubes are produced. From the evaporator the heat would be pumped into the coils of the condenser which, in the ordinary refrigerator, is located outside the cabinet. The temperature of the condenser would be raised thereby to perhaps 100 deg. F.; consequently the heat would leak out to the exterior atmosphere, from which it would again leak into the house to start a repetition of the cycle.

In the winter season with an outside temperature of say 40 deg. F. this cycle would be reversed. The evaporator would be placed outdoors and would be made to have the temperature of perhaps 30 deg. F. (10 deg. cooler than the outdoor air) and consequently it would draw heat from this air. By the heat pump operation the heat would pass to the condenser, where the temperature would be approximately 100 deg. F. With an internal house temperature of 70 deg. F. this heat would go from the condenser into the room air, and leak thence through the house walls, etc., to the outdoor air. In effect, it would be like an electric refrigerator turned inside out.

Since the heat delivered by the condenser of a refrigerator heat pump is always greater than the heat equivalent of the electric power input by an amount equal to the heat flow into the evaporator, the efficiency is in effect greater than 100 per cent.

Herein lies the operating economy of the heat pump in general and the electric refrigerator heat pump in particular; who knows what its future may be?

Application of Refrigeration to Heating and Cooling of Homes

The Heat-pump Principle—Thermal and Mechanical Analyses—Economic and Technical Problems of Application—Service When Cooling—Service When Heating—Climatic Factors—Costs

By A. R. STEVENSON, Jr., F. H. FAUST, and E. W. ROESSLER

Engineering General Department, General Electric Company

THE possibility of using a refrigerator as a heat pump* to heat houses was first suggested by Lord Kelvin in a paper presented before the Royal Society in 1852. [1] Recent articles in the technical press indicate considerable interest in this idea since its revival in 1926. [2]

A noteworthy paper [3] by T. G. N. Haldane, of Scotland, is exceptionally interesting because in it he describes an installation of a refrigerator in his own home for cooling the air in summer and heating it in winter.

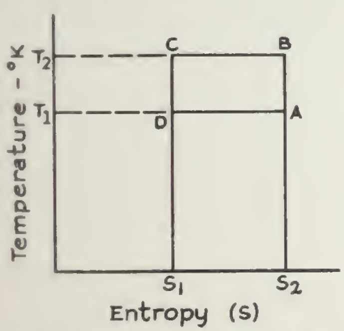

Fig. 1. Diagram of the Operating Cycle of a Perfect Heat Engine

During this present winter, a large-size installation is being tried out by the Southern California Edison Company in its office building at Los Angeles (Calif.). [4] Four 200-hp. synchronous-motor-driven compressors have been installed to cool the building in summer, and are being used to heat it in winter when the outdoor temperature is 42 deg. F. or higher. When the outdoor temperature falls below 42 deg., it is planned to use electric resistance heaters.

In a private home in Tucson (Ariz.), heat-pump equipment has been installed by the Mechanical Heating Company of Los Angeles.

It is not intended, in the present article, to go deeply into the theory of refrigerating machines. Attention is called simply to the fact that a refrigerating machine is a heat pump. For example, in a large ice plant the input to the motor driving the ammonia compressor is about 43 kw-hr. for each ton of ice produced. The heat equivalent of 43 kw-hr. is 147,000 B.t.u. The amount of heat which must be removed from one ton of water at 32 deg. F. to transform it into ice at 32 deg. is 288,000 B.t.u. Thus, by an electrical input equivalent to only 147,000 B.t.u., it is evident that at least 288,000 B.t.u. were extracted from the water at 32 deg. The reasons why 288,000 B.t.u. can be extracted with an expenditure of only 147,000 B.t.u. will be explained later in this article. Here, it is sufficient to say that actual tests prove these figures to be approximately correct.

The ratio of the heat absorbed to the heat expended, or the coefficient of performance of this ice plant as a refrigerator, is therefore at least 1.96. In refrigeration, the heat given off in the condenser is approximately the sum of the heat absorbed from the ice plus the heat equivalent of the input to the motor. The coefficient of performance of this ice plant used as a heater is therefore 2.96. In other words, the ice plant delivers almost three times as much heat to the condenser as the heat equivalent of the electric input to the motor. It is in this manner that a refrigerating mechanism can be used as a heat pump.

The theoretical justification of the phenomenon of a refrigerator absorbing an amount of heat greater than the heat equivalent of the applied power is found in Carnot's Law of Thermodynamics, which was formulated about a century ago. [5] According to this law, the operating cycle of a perfect heat engine can be represented as in Fig. 1, in which entropy is plotted as abscissas and absolute temperature in degrees Kelvin as ordinates.

Since a refrigerator may be regarded as a reversed Carnot engine in which heat energy is absorbed at

This article was presented by the authors as a paper at the joint convention of the A.S.R.E. and A.S.H.V.E., Cleveland (O.), January 28, 1932. —EDITOR.

*A pump is defined in the dictionary as a mechanical device for raising, circulating, exhausting, or compressing a fluid. Strictly speaking, there is no such thing as a heat pump because heat is a manifestation of energy and, consequently, it is not physically circulated or compressed by a refrigerator. Actually, however, a refrigerator increases thermal potential and by analogy it is easily comprehended as a heat pump.

(1) Thomson, William (Lord Kelvin) "On the Economy of the Heating and Cooling of Buildings by Means of Currents of Air," *Glasgow Phil. Soc. Proc.*, v. 3, Dec., 1852.

(2) Stevenson, A. R., Jr., "Cooling Homes, A Field for Refrigeration," presented at the symposium of the Refrigeration with Gas Commiittee of the American Gas Association, April 20, 1926.

(3) Haldane, T. G. N., "The Heat Pump—An Economical Method of Producing Low-grade Heat from Electricity," *Electric Review*, v. 105, pp. 1161-1162, Dec. 27, 1929, and *I.E.E. Journal*, v. 68, pp. 666-675, June, 1930.

Haldane, T. G. N., "Reversed Refrigerating Cycle for House Heating," *Electrical World*, p. 782, April 25, 1931.

(4) Doolittle, H. L., "Edison Building Heated and Cooled by Electricity," *Power*, v. 74, pp. 348-351, Sept. 8, 1931.

(5) Carnot, Nicholas Leonard Sadi, "Reflexions sur la Puissance Motrice du Feu et sur les Machines Propres a Developper Cette Puissance," Paris, 1824. Translated by R. H. Thurston, 1890, John Wiley and Sons, N. Y.

temperature T_1 and dissipated at temperature T_2 as a result of mechanical work done, the coefficient of performance of a perfect machine would then be given by the formula

$$\text{c.p.} = \frac{\text{Area } ADS_1S_2}{\text{Area } ABCD} = \frac{T_1}{T_2 - T_1} = \frac{\text{Refrigerating effect at } T_1}{\text{Heat equivalent of work done}}$$

A temperature difference is necessary for a transfer of heat, and in an ice plant the ammonia would have to be about 10 deg. F. in order to freeze ice rapidly at 32 deg. F. The heat pumped out of the ice would probably be delivered to the surrounding air through a cooling tower which would very likely run at a temperature of about 110 deg. F. Then:

$$T_1 = 10 + 460 = 470$$
$$T_2 = 110 + 460 = 570$$

Substituting these figures, the Carnot theoretical coefficient would be

$$\text{c.p.} = \frac{470}{100} = 4.7$$

It is thus seen that the ice plant which had a coefficient of performance of 1.96—which, at first glance, seemed to be impossible—was only half as efficient as a theoretically perfect, reversed heat engine would have been, operating between the same temperatures.

The coefficient of performance as a heater is always one unit larger than the coefficient of performance as a refrigerator.

In an attempt to explain this paradox for electrical engineers, in a paper on refrigeration,[6] an electrical analogy was given.

A hydraulic analogy would be as follows: Consider a reservoir of water 50 ft. above the ground and another reservoir of water 10 ft. below the level of the ground. A quantity of water at the ground level is required. If water from the 50-ft. elevation is allowed to flow down directly, the only water received at the ground is that which came from the 50-ft. reservoir. This corresponds to the direct conversion of electricity to heat. If, however, we allow the water at the 50-ft. level to flow down through a perfect turbine waterwheel which is connected to a perfect pump, the power developed when 1 cu. ft. of water flows through the waterwheel from the 50-ft. level will be sufficient to pump 5 cu. ft. of water up to the ground level from the lower reservoir 10 ft. below the ground. With this arrangement, for every cubic foot of water that flows from the principal reservoir, 6 cu. ft. of water are received at the ground level.

Reasons for Slow Progress

In view of the fact that the coefficient or ratio of performance of a refrigerating machine is always greater than one for heating, and may be theoretically as high as 10.4 for operation between 45 deg. F. and 100 deg. F., why is it that this method of heating has not been in commercial use since it has been known and recognized ever since the days of Lord Kelvin? The following may be some of the principal reasons:

(1). No suitable refrigerating machine with the necessary characteristics of safety, quietness, lack of vibration, freedom from service, and high efficiency, has been available commercially in sizes of 5 to 25 hp. Machines of this size have been bulky and lacking in automatic features.

(2). The cost of electricity in most localities has been too high until recently to make this method of heating compare favorably with existing methods. Perhaps there has been some blindness to the economic possibilities already here with the gradual introduction of lower rates for electric ranges, hot-water heaters, and domestic refrigerators.

(3). Very little has been known of the actual operating costs of a refrigerating heating system because of the special nature of the refrigerators and auxiliary equipment needed, and the careful study of climatic conditions which is required to predict their performance.

(4). Very little has been known of the first cost of equipment for heating and cooling electrically because of the special nature of the equipment, but it seems fairly certain that it will be considerably higher than the first cost of most of the conventional methods now in use.

(5). People have not yet been educated to the needs of air conditioning, including refrigeration. Until they demand cooling equipment, there is little or no advantage of supplying refrigerating equipment for heating only.

Difficulties

In most methods of heating houses, the efficiency of the heating devices is more or less independent of outdoor temperature. More heat is required in cold days, but the efficiency of the source of heat is not impaired by the lower outdoor temperature, and, in many cases, is higher under these overload conditions than when the heating plant is only lightly loaded in milder weather.

This is not the case, however, when the electric heat pump is used to pump heat into the house, if we use as a source of heat the outdoor air which is an obvious and universal source of low-temperature heat that costs nothing except for the fan power required to blow it over the heat transfer surfaces. Of course, if there is a good supply of relatively warm water available, such as the ocean, a river, a lake, or an underground well, from which the heat pump can abstract heat at a temperature, more or less independent of the outdoor temperature, this difficulty could be avoided. It is not likely, however, that cities would permit the

(6)Stevenson, A. R., Jr., "Refrigeration," *Journal of the Franklin Institute*, v. 208, pp. 143-187, Aug., 1929.

use of their water supplies for this purpose and, therefore, in most cases the atmosphere would have to be used as a source of heat.*

When the outdoor air is used as a source of heat, the size of the machine and the energy consumed in pumping the heat are both very dependent upon the temperature difference. Three difficulties are encountered:

(1). The capacity of the machine is reduced on the days when heat is most needed. Therefore, to take care of these overloads encountered during severe cold spells, the machine must be much larger in proportion.

(2). The efficiency when carrying overloads during the coldest weather is greatly reduced.

(3). When the transfer surfaces absorbing heat from out of doors are below the freezing point, frost will collect on them, impairing the transfer of heat.

The first of these disadvantages—*viz.*, that the machine has reduced capacity in cold weather—can be partially overcome in several ways:

(*a*). The compressor may be equipped with a multi-speed motor which can be run faster in cold weather to increase the capacity of the machine.

(*b*). It might be possible, in mild weather, to store some heat either in large tanks of hot water or in the latent heat of change of state of some material which could be used to help heat the house in cold weather. This storage method could only be relied upon after a very thorough study of the weather, leading to a reliable prediction as to the length and severity of the cold spells through which the heat storage must be used without being completely exhausted.

(*c*). An auxiliary form of heat might be supplied which would be used only in extreme weather. This might be coal, oil, gas, or electric resistance heaters. It is somewhat unlikely that the public utilities would be willing, even at high rates, to furnish either gas or electricity for this type of emergency heating, which would tend to create a bad peak load on their lines.

The second objection—*i.e.*, the low efficiency when carrying overloads—is not so serious as the first one. It may be stated conversely as an advantage—*i.e.*, the efficiency is greatly improved in mild weather, whereas most other heating systems are very inefficient in mild weather. Thus, in a climate where cold spells are short compared with long stretches of mild weather, the advantage of high efficiency during long continued mild weather might more than overbalance the decreased efficiency during cold spells of short duration.

The third difficulty—*viz.*, frosting of heat transfer surfaces—would not be encountered when these surfaces are above freezing; at the other extreme, during very cold weather when the moisture content of the outdoor air is very low, there might not be much trouble due to frost. But in intermediate temperatures, when the transfer surfaces are just below the freezing point (particularly on foggy days near the critical temperature at which airplane wings collect ice), frost might form very rapidly. The use of a spray tower with brine instead of water would be one way of eliminating this problem of frost, but the brine would be gradually diluted. There are also several other methods, such as intermittent defrosting, flexing the heat transfer surface to crack off the ice, and so on.

*It has been suggested that the latent heat of the water be extracted by freezing it. In Washington (D. C.) the amount of ice formed during the winter in heating a 14,000-cu. ft. well-insulated house would be 210 tons, or 7800 cu. ft., which would make a pile about half the size of the house.

Operating Conditions

It is thus seen that the design of electric heat-pump apparatus for heating and cooling houses is very dependent upon operating conditions, and especially dependent upon the climate in which the apparatus is to be operated.

In studying these requirements, it must be borne in mind that the chief advantage of this complicated and high-first-cost type of installation lies in the combination of heating and cooling. In bringing out a high-cost apparatus for this dual purpose, the other aspects of air conditioning should also be included. It therefore seems wise, in the statement of this problem, to include a brief review of air conditioning and then a brief review of the climate in various parts of our country before attempting to specify the proper characteristics for a heat-pump installation.

In reviewing this subject, it is interesting to note the prediction of Dr. Charles Proteus Steinmetz, who wrote in 1915, as follows: "When heating is done electrically, if I want 70 deg. in my home, I shall set the thermostat at 70 and the temperature will not rise above that point. This temperature will be maintained uniformly without regard to the temperature outside.

"If it is very cold, electric heaters will hold the temperature at 70. If it should be 90, or 100 deg. outside, the same electrical apparatus will cool the air inside. In this way, we shall have a uniform temperature in our homes throughout the year.

"Besides temperature, we have to suffer from humidity, or from dryness of the air. This is especially true with the present-day furnace. With electric equipment, we shall be able to control this and have humidity normal at all times. This electric equipment will have an absolutely automatic control of both temperature and humidity.

"Ventilation doesn't exist in the average home today. At present, we have to depend upon the windows and doorways, or we turn on an electric fan to blow the bad air out. When electricity is developed, we shall have apparatus that will destroy the bad air, bring fresh air into the home, and when the air outside is not sufficiently invigorating, automatically arrange

a distribution of ozone. We shall constantly have good, fresh, pure air indoors."[7]

Air conditioning, as applied to enclosures for human occupancy, has been defined as the science of controlling the temperature, humidity, motion, and cleanliness of air to maintain the most suitable conditions for the comfort, health, and happiness of human beings.

Much of the success in air conditioning of theatres, restaurants, office buildings, and other public places, may be traced back to the pioneer work of Carrier.[8]

The next step in air conditioning with which the present article is particularly concerned, is the air conditioning of private homes. Already, several methods have been developed commercially for automatically heating homes, but practically nothing has been done commercially to cool homes.

In the study of air conditioning, we are mainly interested in the dissipation of waste heat from the body and its automatic control.

(7) Steinmetz, Charles, Popular article on automatic heating and cooling of houses, *Ladies' Home Journal*, Sept., 1915.

(8) Carrier, Willis H., "Rational Psychrometric Formulæ," *Trans. Am. Soc. Mech. Engrs.*, Vol. 33, p. 1005, 1911.

It is an interesting fact that the amount of heat dissipated by the average person is practically constant at 400 B.t.u. per hr. over a wide range of temperatures and humidities. Under normal conditions of temperature and humidity, Yaglou[9] states that heat is dissipated approximately in the following proportions:

Radiation, conduction, and convection	73	per cent
Evaporation of moisture from skin	14.5	" "
Evaporation of moisture from lungs	7.2	" "
Warming of inspired air	3.5	" "
Warming the food ingested	1.8	" "

When the temperature is raised to 86 deg., the radiation and conduction has been shown to drop from 76 to 38 per cent, and the heat dissipation by evaporation from the skin and lungs, to rise from 24 to 62 per cent. Obviously, at approximately 100 deg., all the heat would have to be dissipated by evaporation.

The foregoing data show that one cannot consider heating and cooling without also considering humidity.

(9) Yaglou, C. P., "The Heat Given Up by the Human Body and Its Effect on Heating and Ventilating Problems," *Transactions, A.S.H.V.E.*, Vol. 30, pp. 365-376, 1924.

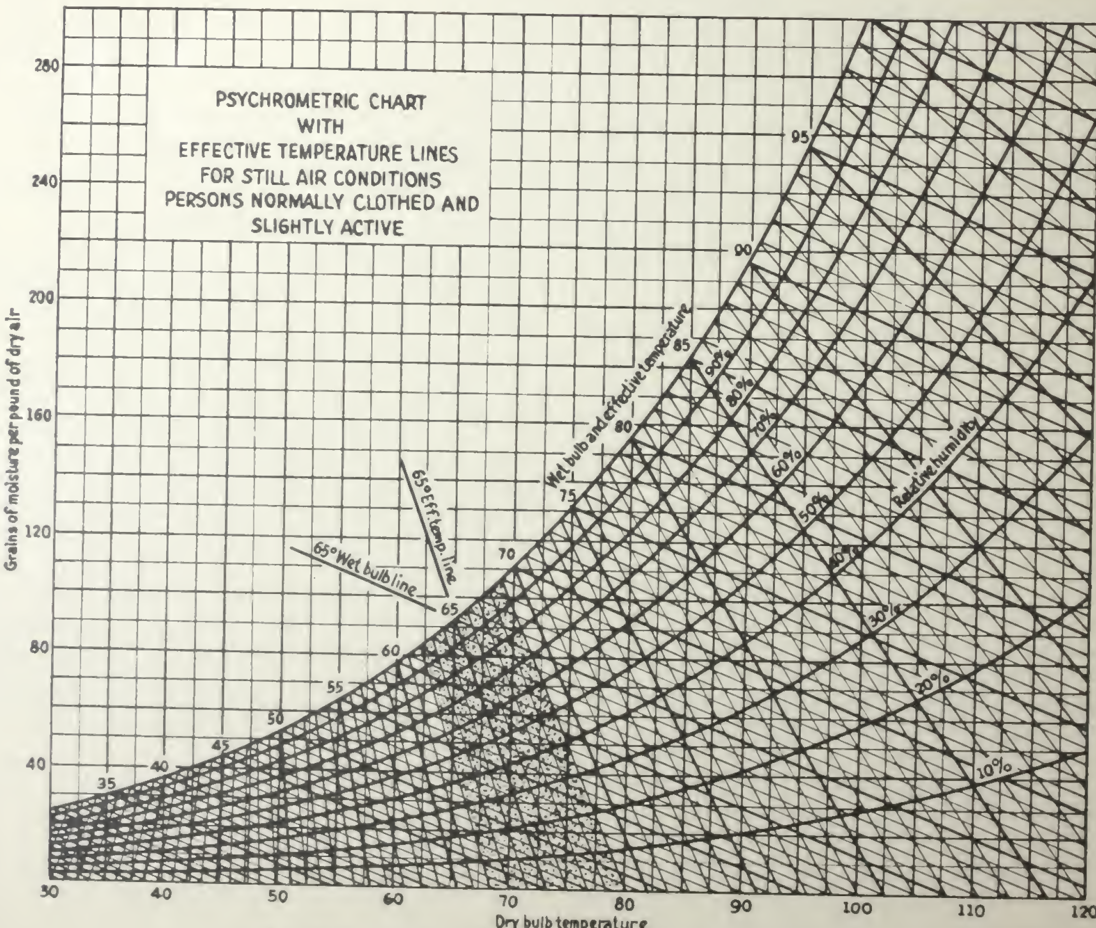

Fig. 2. Psychrometric Chart. The comfort zone is represented by the dotted area

The American Society of Heating and Ventilating Engineers has developed a scale of effective temperature to correlate the effect of temperature, relative humidity, and air motion on human comfort. For instance, equal comfort is experienced at 65 deg. F. and 100 per cent relative humidity, as at 72.5 deg. F. and 10 per cent humidity. So the effective temperature is said to be 65 deg. in both cases. A psychrometric chart [10] showing effective temperature lines is shown in Fig. 2.

It is important to note that conditions best suited for comfort in winter may be, and usually are, not the best suited for comfort in summer. The explanation may be found in the fact that the human body is better able to make adjustments for cold weather than for warm weather. In temperatures below zero, a fair degree of comfort may be obtained by insulating the body with sufficient clothing. In passing from the cold outside to a hot room, an adjustment is made by removing some of the clothing. In summer, only a limited adjustment may be made by adding or removing clothes.

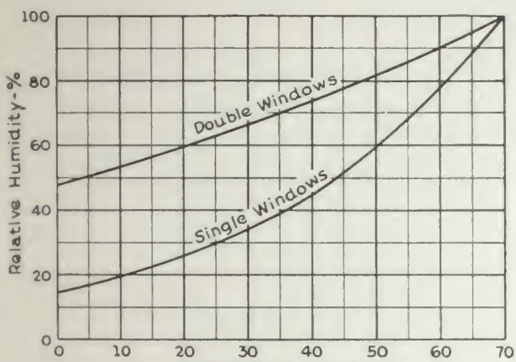

Fig. 3. Per Cent Relative Humidity at 70 deg. F. at Which Condensation on Windows Begins

The general practice in winter seems to be to hold the house as accurately at 70 deg. F. as possible, without any regard for humidity. If the humidity can be increased somewhat, it would probably be healthier to hold the house at 68 deg. In fact, Ellsworth Huntington, who has studied the effect of climate upon civilization, [11] states that 63 deg. outside temperature is the optimum temperature with the humidity held as high as possible. Unless double windows are put on the house to prevent condensation of moisture, it is probably impossible to raise the humidity high enough to make one comfortable at 63 deg. In winter, an effective temperature of 65 deg. is recommended by many air conditioning engineers. There are apparently no conclusive data with regard to the effect of humidity on health. It is admitted that the humidity in our steam-heated homes in winter is far too low, and it is believed that a higher humidity would be beneficial. It would probably be wise to try to keep the humidity as near 50 per cent as possible without causing condensation on the window panes. Fig. 3 has been prepared, showing the values of per cent relative humidity which will cause condensation on window panes at various outdoor temperatures.* It is interesting to note that, since normal winter humidities run as low as 10 to 20 per cent, practically no humidification may be accomplished in houses with single glass windows until outdoor temperatures reach 10 deg. or above.

At first thought, it might seem desirable in summer to cool the house to 70 to 75 deg., even during extreme 90 to 100 deg. weather. Experience has taught, however, that this imposes too much of a shock on the body in going into and out of the cooled room. Instead, the indoor conditions should be balanced against outdoor conditions, and probably in no case should the temperature and humidity be lower than that shown in Table I. [10]

TABLE I
CONDITIONS RECOMMENDED FOR HOUSE COOLING
(A. S. H. V. E.)

Outside Temp. Deg. F.	Dry Bulb Deg. F.	Wet Bulb Deg. F.	Effec. Temp. Deg. F.	Relative Humidity Per Cent	Grains of Moisture Per Lb. Dry Air
95	80.0	65.2	73.4	45.0	69.0
90	78.0	64.5	72.2	47.5	69.0
85	76.5	64.0	71.1	50.0	69.0
80	75.0	63.5	70.2	52.5	69.0
75	73.5	63.0	69.3	56.0	69.0
70	72.0	62.5	68.2	60.0	69.0

Indications from this table are that a constant value of moisture content of 69 grains per lb. of dry air is desirable.

Having reviewed the optimum indoor conditions winter and summer, it now becomes necessary to investigate what outdoor conditions will be encountered in various parts of the country. Figs. 4, 5, 6, and 7 show the climate in various of our leading cities.

Cooling the Whole House

In a climate such as Washington (D. C.), a refrigerating machine of 2.5 tons capacity might be required for an average small home. The refrigeration could be supplied by a compression refrigerating machine or by an absorption machine. A comparison of operating costs for these two methods follows:

(1). A 2.5-ton electrically-driven compression refrigerating machine would have an input of about 4 kw. To run it one day would require 96 kw-hr., which at 2 cents per kw-hr. would cost $1.92. Such a machine, installed in the basement, would be cooled by air circulation from the outside and no water would be required.

(10) "Guide," The American Society of Heating & Ventilating Engineers.
(11) Huntington, Ellsworth, "Civilization and Climate," 3rd edition.

*These curves are based on still air conditions inside the window and a wind velocity of 10 to 15 miles per hr. outside. Increasing the air velocity inside the window would increase the glass temperature and permit higher humidities to be maintained. A velocity of only 175 ft. per min. inside a single-glass window would permit a relative humidity of 24 per cent at 70 deg. F. to be maintained on a 10-deg. day instead of 19 per cent, as from the curves. This increased humidity would be attained, however, by an increased heat loss through the window of 12 per cent.

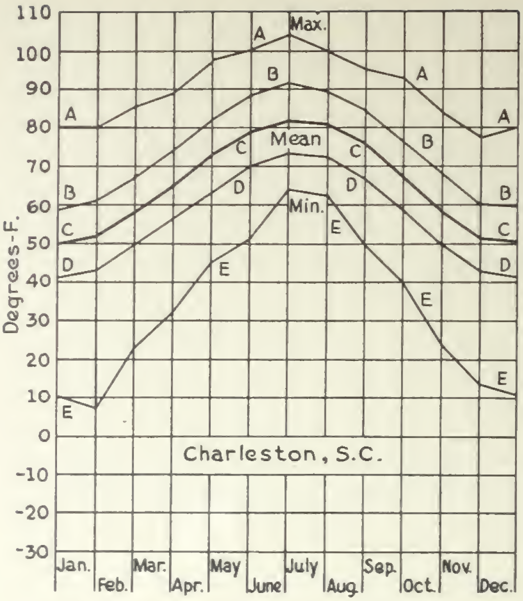

Fig. 4. Climatic Temperatures at Charleston (S. C.), from Monthly Records Covering 31 Years

AAA: Maximum ever recorded during month
BBB: Mean (*CCC*) plus one-half average daily variation
CCC: 31-year mean temperature
DDD: Mean (*CCC*) minus one-half average daily variation
EEE: Minimum ever recorded during month

(2). A gas-heated absorption machine of the same capacity would in 24 hr. consume 3000 cu. ft. of manufactured gas (550 B.t.u. per cu. ft.), which at 75 cents per 1000 cu. ft. would cost $2.25. This machine would probably be water-cooled and would consume about 14,000 gal. of water per day. Water in Washington (D. C.) costs 6 cents per 100 cu. ft. When this study was made, therefore, the cost of water for a day would be $1.15, and the total cost, including the water, would be $3.40.

In Charleston (S. C.) the water costs 17 cents per 100 cu. ft., and the cost of water, instead of being $1.15, would be $3.20, making a total of $5.45.

If it were attempted to make this gas-heated absorption machine air cooled, although the cost of water would be saved, the cost of gas would probably be increased about 60 per cent which, plus the cost of running condenser and absorber fans, would bring the total cost up to about $4.00 (see appendix).

These figures would tend to show that the electric system has some advantage from the standpoint of operating costs over the gas system for cooling.

Heating the Whole House

At 75 cents per 1000 cu. ft., gas is a slightly cheaper form of heat than the electric heat pump at 2 cents per kw-hr. Table II shows some calculations which have been made, using the climate curves shown in Figs. 4, 5, 6, and 7, and a degree-day chart. [12]

[12] "Degree-day Chart," American Gas Association.

It will be noted that, in the climate of Washington (D. C.) the gas equipment the year round costs 6 per cent less than the electric equipment; but as one goes farther south, the year-round operating cost of the electric equipment is much lower than that of the gas equipment. Here again, it should be particularly

TABLE II

SUMMARY OF COMPARATIVE ANNUAL COSTS OF HEATING AND COOLING A 14,000-CU. FT. WELL-INSULATED HOUSE BY ELECTRIC HEAT PUMP AND BY GAS

	Washington	Charleston	Los Angeles	New Orleans
Heating				
Electric heat pump	$232	$84	$71	$48
Gas burner	199	77	66	46
Cooling				
Electric heat pump	25	52	21	56
Gas-heated absorption machine	41	142	44	98
Heating and Cooling				
Electric heat pump	257	136	92	104
Gas burner and absorption machine	240	219	110	144

noted that the electric equipment runs solely on electricity, whereas the gas equipment in summer consumes a large amount of water, the cost of which is included in Table II. (See appendix.)

In studying the cooling requirements, we have assumed a 2.5-ton capacity machine. In Washington (D. C.), we need a machine of double this capacity

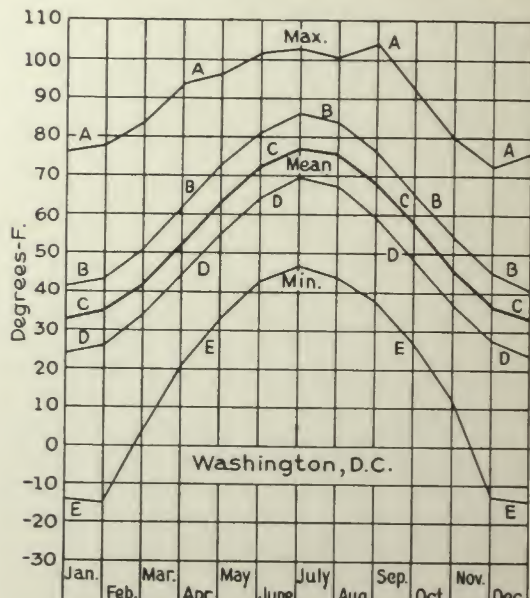

Fig. 5. Climatic Temperatures at Washington (D. C.), from Monthly Records Covering 31 Years

AAA: Maximum ever recorded during month
BBB: Mean (*CCC*) plus one-half average daily variation
CCC: 31-year mean temperature
DDD: Mean (*CCC*) minus one-half average daily variation
EEE: Minimum ever recorded during month

to carry the heating load on the peak days. This could be accomplished by designing the machine with a two-speed motor to take care of these overload conditions.

Under electric heating, the estimates also include the cost of running fans to circulate the air in the house, using a 100-deg. source of heat; whereas in the cost of heating with gas, it has been assumed that the source of heat would be of a sufficiently high temperature that no fans would be required except for cooling.

In making the calculations, the thermal leakage for heating was estimated to be 1044 B.t.u. per hr. per deg. F., and for cooling, because of dehumidification and probable air leakage, at 1.85 times this.

The heating requirements were figured from the degree-day chart. (12)

The cooling requirements were first figured on the basis of cooling to 70 deg. F. from the average temperature plus one-half the average daily variation in temperature for one-half the time, and then modified as follows: Cooling for comfort does not require cooling to 70 deg. F. From the recommended temperatures in Table I, the cooling should be about 60 per cent of the difference between the outdoor temperature and 70 deg. Probably 50 per cent instead of 60 per cent would be ample. Therefore, the figure used in preparing Table II was taken as one-half the refrigeration required to hold 70 deg. Under this assumption, even in the warmest parts of the United States, a refrigerating machine large enough to heat a house, would be large enough to cool it.*

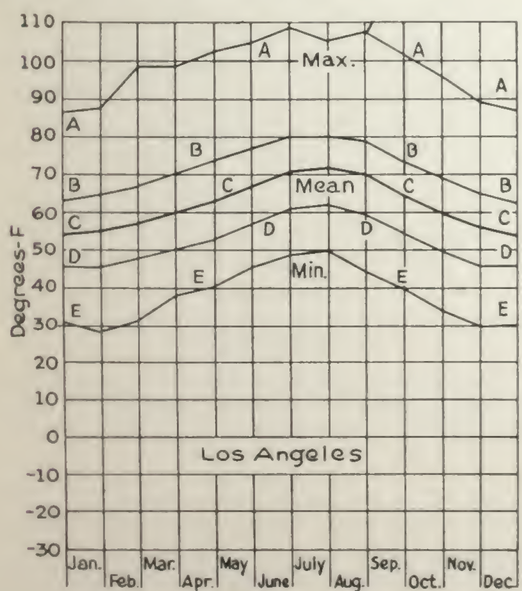

Fig 6. Climatic Temperatures at Los Angeles (Cal.), from Monthly Records Covering 31 Years

AAA: Maximum ever recorded during month
BBB: Mean (*CCC*) plus one-half average daily variation
CCC: 31-year mean temperature
DDD: Mean (*CCC*) minus one-half average daily variation
EEE: Minimum ever recorded during month

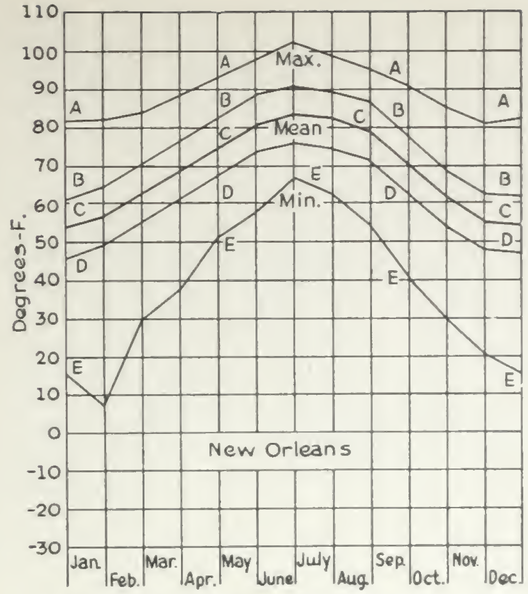

Fig. 7. Climatic Temperatures at New Orleans (La.), from Monthly Records Covering 31 Years

AAA: Maximum ever recorded during month
BBB: Mean (*CCC*) plus one-half average daily variation
CCC: 31-year mean temperature
DDD: Mean (*CCC*) minus one-half average daily variation
EEE: Minimum ever recorded during month

The cost of operation, as given in Table II allows 1000 watts for the power requirements of the two fans and the pump which are necessary. About 2000 B.t.u. are liberated in the house by these auxiliaries. This is credited to the heating output, and deducted from the cooling output.

The actual efficiency of the heat pump is not expected to be very high. On a 20-deg. day, for example, the estimated coefficient of performance of the pump as a heater is 2.7. The desired temperature to which the heat is to be pumped is 70 deg., and, from the Carnot cycle, the theoretical coefficients of performance as a heater should be 10.6. The heat pump which we have assumed is therefore only 25 per cent as efficient as a theoretically perfect one. A considerable proportion of this loss occurs in the heat exchangers and the auxiliaries, and the relative efficiency of the heat pump itself is about 50 per cent.

When electric heat pumps for heating houses are being developed, the following suggestions might be borne in mind: The vapor compression system is considered the most desirable and has been used as the basis of the calculations. It is more efficient than the use of air or other perfect gases as refrigerants, although the latter have an advantage from the standpoint of safety. The absorption system requires heat rather than mechanical work as a source of

*The least severe heating condition in the U. S. is at Key West (Fla.) where the lowest outdoor temperature recorded is 40 deg. To heat a well-insulated 14,000-cu. ft. house at such a time would require 31,400 B.t.u. per hr. To cool this house on a 95-deg. day to 80 deg. would require 29,000 B.t.u. As the heat pump when cooling would work with an evaporator temperature of about 45 deg., and of 20 deg. or so when heating, its capacity as a cooler should be quite adequate.

energy, and the coefficient of performance would be very low if an electrically-heated absorption machine were used. Table III shows the performance of large vapor-compression, dense-air, and absorption machines.

Heating Distribution System

The low temperature at which the heat pump must deliver this heat will require radical departures from the ordinary heating system. Radiators of the ordinary type would be very large* and would have to be fitted with drip pans to carry away the moisture condensed from the air when used for cooling in the summer. Unless placed near the ceiling, they would tend to form a blanket of cold air over the floor without lowering the temperature at the breathing level.

If fan-equipped radiators or unit heaters were used, the size would be considerably reduced and the temperature distribution in the rooms improved. In this system, hot water would be circulated for heating in winter and cold water for cooling in summer. Steam at high vacua would probably not be used for heating, as means for water circulation for cooling would already be available, and owing to trouble from air leaking into the radiators it would be difficult to run a vacuum system at the low temperature required for efficiency.

A central warm-air system with fan circulation would allow air conditioning to be done in one central unit. A circulation of about four times that of the ordinary gravity warm-air system would be necessary in order to keep the temperature of the air heater down to 100 deg. F.† even in a well-insulated house. Since fan circulation will permit of two to three times the air velocity in the ducts, the duct work will not be more than twice the normal size, and this appears quite feasible.

Panel warming has recently attracted much attention, and is an ideal way of heating with low-temperature heat. It would probably not be entirely satisfactory for cooling, as moisture might condense on the walls or ceiling. It might very well be used as an auxiliary heating means in connection with a central warm-air system in order to keep down the size of ducts, and would not be used for cooling at all.

No attempt is made in this article to say what the first cost of electric heat-pump apparatus would be, since cost of apparatus depends so much on the stage of development and the quantities produced. All new devices come on the market at relatively high prices, and then the prices come down as the field is developed. The prospect of heating houses with heat pumps does not look very attractive economically in the northern part of the country where the temperature differences are high.

For the southern half of the country, however, Table II would seem to indicate that, neglecting the first cost of installation, from an operating cost standpoint alone wherever a 2-cent electric rate is available, the electric heating and cooling of houses is practical. The real advantage in the use of a refrigerating machine comes in the cooling which cannot be accomplished in any other way. The public must be "sold" on the need for cooling before it will consider the installation of refrigerating machines in its houses. Having thus sold a cooling equipment, it would be possible to call attention to the fact that, in the southern parts of the country, this same cooling equipment could be used to heat the house in winter if proper arrangements were made.

The efforts of refrigerating engineers should therefore be concentrated in the near future on the development of refrigerating apparatus for cooling houses.

TABLE III

PERFORMANCE OF REFRIGERATING MACHINERY

	Ammonia Ice Plant	Dense Air Machine	Ammonia-Water Absorption System
Evap. temp., deg. F.	−10	−82	0
Cond. temp., deg. F.	84.5	62	91
Theoretical c. p.	4.76	2.62(a)	5.05
Lb. steam per hr. per ton refrigeration			32.8
Refrig., B.t.u. per hp., steam cylinder	6090.	1554.	
Actual c. p.	2.39	0.611	0.381
Efficiency, per cent by Carnot	50.3	23.3(a)	7.55(b)

(a) Based on temperatures as given of air entering and leaving expansion cylinder. Actually the effective cooling temperature is higher and the theoretical coefficient of performance (c. p.) is greater.
(b) Based on electric heating of generator.

APPENDIX

PERFORMANCE OF GAS-HEATED ABSORPTION MACHINE

The absorption machine combines a heat engine and a refrigerating compressor in one unit. The heat engine part has a theoretical efficiency of

$$\frac{T_2' - T_1'}{T_2'}$$

and the refrigerating compressor has a theoretical coefficient of performance of $\dfrac{T_1}{T_2 - T_1}$

where T_2' = generator temperature in degrees K.
T_1' = absorber temperature in degrees K.
T_2 = condenser temperature in degrees K.
T_1 = evaporator temperature in degrees K.

*The heat emission of the ordinary cast-iron radiator varies as the 1.3 power of the temperature difference between the room and the heating fluid (*A.S.H.V.E. Guide*). With 100-deg. F. water instead of 215-deg. F. steam in a 70-deg. F. room, the ratio of outputs would be

$$\frac{H_{100}}{H_{215}} = \left(\frac{100-70}{215-70}\right)^{1.3} = 0.129$$

Therefore, $\frac{1}{0.129}$, or 7.75 times as large a radiator would be required as if steam were used.

†In the research residence at the University of Illinois (Bulletin No. 189), which is heated with a warm-air gravity system, about 91,000 B.t.u. per hr. are required on a 10-deg. day. An air circulation of 820 c.f.m. at 146 deg. F. at the furnace bonnet is required to heat the house to 70 deg. F. A well-insulated house heated to 70 deg. by a heat pump would on a 10-deg. day require 60,000 B.t.u. per hr., and if all this were supplied by air at 90 deg. F., it would require 3.5 times as much air for the well-insulated house. The duct velocity in the research residence, however, is only 175 ft. per min., and if with fan circulation 400 ft. per min. were used, it would only require 53 per cent more duct area to care for this increased volume.

The overall coefficient of performance of the absorption machine, therefore, should be

$$\frac{Q}{I}=\frac{\text{refrigeration}}{\text{heat input}}=\frac{T_2'-T_1'}{T_2'}\times\frac{T_1}{T_2-T_1}$$

Relatively few data on absorption machines are available. It is stated [13] that 33 lb. of steam per hour at 20 lb. pressure and 6 gal. of cooling water per minute are required per ton of refrigeration, with 15-deg. F. brine and 85-deg. F. cooling water.

TABLE A: WATER COSTS

	Weighted Average Summer Temp., Deg. F.	Water Used, Cu. Ft. Per 1,000,000 B.t.u. Refrigeration	Cost Dollars Per 100 Cu. Ft.	Water Cost, Dollars Per 1,000,000 B.t.u. Refrigeration
Washington.....	75.6	2060	0.06	1.24
Charleston......	80	2570	0.17	4.36
Los Angeles.....	71.5	1700	0.12	2.04
New Orleans....	77.5	2280	0.075	1.71

Assuming the temperatures in the machine to be: generator, 220 deg. F.; condenser and absorber, 100 deg. F.; evaporator 10 deg. F., the theoretical coefficient of performance is

$$\frac{220-100}{460+220}\times\frac{460+10}{100-10}=0.922$$

The heat required theoretically per ton refrigeration is therefore 12,000/0.922 = 13,000 B.t.u. per hr.

Actually 33×962 = 31,800 B.t.u. per hr. are required, so that the efficiency is actually 13,000/31,800 = 40.9 per cent.

Assuming that the same efficiency will apply to machines with a 35-deg. F. evaporator, the coefficient of performance will be

$$\frac{Q}{I}=\frac{220-100}{460+220}\times\frac{460+35}{100-35}=1.34 \text{ theoretical}$$

and the actual, 1.34×0.409 = 0.55.

[13] Macintire, H. J.: Handbook of Refrigeration (p. 91), John Wiley & Sons, Inc.

Therefore, 1000/0.55 = 1820 B.t.u. of heat will have to be supplied per 1000 B.t.u. refrigeration. If this heat is supplied by burning manufactured gas of 550 B.t.u. per cu. ft., costing 75 cents per 1000 cu. ft. in a gas burner of 79 per cent efficiency, the cost of the heat per 1,000,000 B.t.u. refrigeration will be

$$1.82\times\frac{1{,}000{,}000}{550\times0.79}\times\frac{0.75}{1000}$$

$$=\$3.15 \text{ per } 1{,}000{,}000 \text{ B.t.u. refrigeration}$$

Water Consumption

Six gal. per min. per ton are required with 85 deg. F. water, corresponding to a water consumption of 4000 cu. ft. per million B.t.u. refrigeration. If the water leaves the machine at 95 deg., less water can be used if the inlet water temperature is lower. Table A shows the effect of this on the water cost.

Air-cooled Absorption Machine

If water were not used, the temperatures of the absorber and the condenser would be increased. Assuming that 120 deg. F. instead of 100 deg. F. were used, the theoretical coefficient of performance would be

$$\frac{Q}{I}=\frac{220-120}{460+220}\times\frac{460+35}{120-35}=0.857$$

Therefore, compared with the water-cooled machine, 1.34/0.857 = 1.56 times as much heat would be required. The cost of heat per 1,000,000 B.t.u. refrigeration would be \$4.92, and in addition a fan for condenser and absorber would use, assuming ½ kw. is needed for a 2.5-ton machine,

$$\frac{1{,}000{,}000}{2.5\times12{,}000}\times\frac{1}{2}=16.7 \text{ kw-hr.}$$

which at 3 cents per kw-hr. would cost \$0.50 and raise the cost to \$5.42 per 1,000,000 B.t.u. of refrigeration.

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